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Acute Lung Function Responses to Ambient Acid Aerosol Exposures in Children

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We examined the relationship between lung function changes and ambient acid aerosol episodes in children attending a residential summer camp. Young females (112) performed daily spirometry, and 96 were assessed on one occasion for airway hyperresponsiveness using a methacholine bronchoprovocation test. Air quality measurements were performed on site and four distinct acid aerosol episodes were observed during the 41-day study. The maximum values observed during the 41-day study were: O_3 at 143 ppb; H_2SO_4 at 47.7 μg/m^3; and [H$^+$] at 550 nmole/m^3. Maximum decrements of 3.5 and 7% for FEV_1 and PEF, respectively, were observed to be associated with the air pollution episodes. There was some evidence of a differential lung function response to the episodes where children with a positive response to a methacholine challenge had larger decrements compared to their nonresponsive counterparts.

Introduction

Ambient acid aerosols resulting from atmospheric transformations of primary pollutants may represent a significant health hazard (*1*). Acid aerosols are often observed to be associated with other air pollutants including ozone (O_3), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) (*2*). There have been few epidemiological studies that have specifically addressed the acidic aerosol—health effect hypothesis. Although no one study has clearly associated acid aerosols with observed adverse health responses, there is mounting evidence from both toxicological and clinical studies that suggest that moderate exposures to air pollution mixtures can influence respiratory health and function (*2*).

Air pollution episodes have been observed to be associated with acute mortality and acute and chronic respiratory morbidity (*3*). Evidence that acute respiratory health and function in children is affected by ambient air pollutants at or near current air quality standards has been reported by several investigators (*4–11*). Although the biological evidence for these associations resides principally in transient decrements of lung function, the implications of repeated exposures and subsequent decrements on human respiratory health remain to be determined. It is not clear at the present time whether these changes have causal consequences in the development or promotion of lung disease.

Summer camps have been used by several investigators to assess the influence of ambient air pollution on respiratory health and function of children. Because children are predominantly outdoors and relatively active while at camp, they provide a unique opportunity to assess the relationships between respiratory health and function and concurrent air pollution levels. Raizenne et al. (*10*) have reported short-term decrements in the lung function of children attending a residential summer camp in a region receiving a mixture of air pollution, including acid aerosols. Lung function decrements were associated with O_3, fine particles (PM2.5), sulfates, and temperature. These decrements were also observed to be associated with 12- and 24-hr time lags. Other investigators (*7,8,11*) have also reported observing decrements in lung function in children at camps to be related to ambient air pollution levels. In one study (*7*), the decrements were most strongly associated with O_3 and were reported to persist for up to 1 week after a 4-day pollution episode having a mixture of pollutants including acid aerosols. Other recent studies indicate that persistent lung function decrements are observed in children after an air pollution episode where SO_2

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and total suspended particulates exceeded 200 μg/m^3 (*12,13*).

The present study was undertaken to examine the relationship between acute exposure to ambient pollutants including O_3, fine particles (PM2.5), sulfates, and sulfuric acid (H_2SO_4) and respiratory function in children.

Methodology

A residential Girl Guide camp located on the north shore of Lake Erie, 50 km southwest of Hamilton, Ontario, was used in this study. There were three consecutive 2-week sessions between June 29 and August 9, 1986. One hundred forty-five young girls between the ages of 8 and 14 were contacted, and 116 agreed to participate in the study activities. Parents were asked to complete a self-administered questionnaire on the child's respiratory health history, parental health, and household characteristics.

Spirometry was performed each day in two mobile trailers located on the camp site. Four 21E Pulmonary Function Workstations (Gould Medical Products, Dayton, OH) were operated by four experienced technicians. The method of testing followed the ATS (*14*) and GAP (*15*) spirometry guidelines for testing of children and incorporated a minimum of five maneuvers (*16*). Children were tested each day between 3:00 P.M. and 5:30 P.M., in a seated position and with noseclips in place. Children came to the test site at approximately the same time each day (± 30 min). Spirometers were calibrated each day before testing and whenever the ambient temperature changed by 2°C during the testing session. Calibration was performed by each technician using a 3-L syringe. All lung measurements were corrected to BTPS (body temperature, pressure, saturated) values. Height and weight were measured at each of the first four lung function tests, and the mean of the four measurements was used to define a unique height and weight for each child.

Methacholine bronchial challenge (MCh) tests were performed on the third or fourth day of each session at the camp site. All parental questionnaires were reviewed by attending physicians at the site prior to the test. Children with a history or current symptoms, i.e., persistent wheeze, asthma, allergy, and recent colds, were scheduled early in the day to monitor possible latent responses. All tests were conducted between 8:30 A.M. and 5:00 P.M. The method of Hargreave et al. (*17*) was used for all bronchial challenges. The maximum concentration used was 16 mg/mL and the maximal response for termination of the test was a 20% decrement in FEV_1. The concentrations of methacholine inducing a 20% decrement in FEV_1 ($PC_{20}FEV_1$) were obtained, and positive methacholine tests (MCh^+) were defined as children having a $PC_{20}FEV_1$ of 8 mg/mL or less. All spirometric assessments associated with the methacholine challenge were performed on two 8-L Collins (Braintree, MA) water-filled spirometers, calibrated each day using a 3-L syringe.

To determine atopy, skin tests were performed using the prick method. Ten common allergens (Table 1) were used, along with negative (diluent) and positive (histamine, 8 mg/mL) controls. Wheal diameter was measured by ruler and caliper and recorded to the nearest 1 mm. A wheal diameter 2 mm or more larger than the response to diluent was regarded as a positive test.

An air pollution monitoring station was operated on-site in a van situated in an open area approximately 10 m from the lung testing trailers. The air pollution trailer housed continuously recording O_3, SO_2, NO_2 monitors, and a thermal speciation flame photometric unit (modified Meloy 285) (*18*), which measured continuously total sulfate (cSO_4^{2-}) and H_2SO_4 ($d_a \leq 2.5$ μm). Ambient air samples for the continuous monitors were made through a Teflon and glass filter mounted from an inlet situated on the roof of the trailer approximately 5 m from the ground. Ten-minute and hourly averages were obtained from the continuous monitors. Two Beckman dichotomous particle samplers located on the roof of the trailer sampled fine ($d_a \leq 2.5$ μm) and coarse ($2.5 \leq d_a \leq 10$ μm) particle mass sulfate and elements using teflon filters. Aerosol strong acidity ([H^+] nmole/m^3) and particle sulfate (SO_4^{2-}) were determined from fine particle mass collected by a Harvard impactor using Teflon filters with ammonia denuders (*19*). Organic and elemental carbon were measured with a second Harvard impactor using prefixed quartz filters. Two 12-hr samples per day (starting 7 A.M. and 7 P.M. EST) were collected from each particle monitor. Meteorology parameters, temperature, dew point, and wind speed and direction were monitored continuously with an hourly averaging point time using a Climatronics modular WM-111 system. Table 2 summarizes the aerometric measurements and the exposure metric definitions. The percent data capture during the 41-day period equaled or exceeded 95% for all parameters.

The influence of air pollution episodes on the lung function of children was examined by determining the difference in lung function for each child between days of high and low pollution. Four distinct intervals of elevated air pollution and the corresponding control days are identified in Table 3. Control days were defined as days with O_3 max ≤ 80 ppb; $SO_4^{2-} \leq 15$

Table 1. Skin prick test: Allergens.

Alternaria tenuis	Grass pollen
Aspergillus fumigatus	*Hormodendrum cladosporiodes*
Cat hair/epithelium	Horse hair/dander
Dog hair/dander mix	Ragweed pollen
Dust mite (Dermatophagoides farinae)	Tree pollen

Table 2. Pollutant exposure metrics.

Pollutant, units	Method
O_3, ppb	Chemiluminescence 1 hr maximum is maximum hourly value for 12-hr period, 7 A.M.–7 P.M.
PM 2.5, $\mu g/m^3$	Dichotomous sampler 12-hr integrated sample (mass), 7 A.M.–7 P.M.
SO_4^{2-}, $\mu g/m^3$	Harvard impactor (with denuder inlet)
$[H^+]$, nmole/m^3	12-hr integrated sample, 7 A.M.–7 P.M. Total sulfate and aerosol strong acidity
H_2SO_4, $\mu g/m^3$	Modified Meloy 285 [Allen et al. (*18*)] Flame photometry Continuous (10 min/1-hr averages)
Temperature, °C	Mean of hourly measurements over 12-hr period, 7 A.M.–7 P.M.
Relative humidity, %	Average % relative humidity over 12-hr sampling period, 7 A.M.–7 P.M.

$\mu g/m^3$; $H_2SO_4 \leq 10\ \mu g/m^3$ (or $[H^+] < 55$ nmole/m^3). Note that there were two episodes identified in session 2. The difference between the lung function response on the episode day and the average of the responses on the corresponding control days was determined for each child and each of the responses separately. The distribution of these differences across children was examined. The mean of the differences were then tested to differ from zero by a one-sided *t*-test. A similar procedure was performed separately by methacholine response.

Results

Subject characteristics are presented by session in Table 4. A total of 112 children (77.2% of contacted) participated in the study. Of those initially contacted, 20% refused to participate, one never attended, two left camp early, and one subject withdrew from the study. Five children were reported to have doctor-diagnosed current asthma (from parental questionnaire), five did not perform the methacholine and allergy test, and six children did not perform either the methacholine or the allergy test. Excluding the five asthmatics, a cohort of 96 children had complete data on all health components.

For the 107 nonasthmatic girls with daily lung function results, a summary of the daily lung function responses is presented in Figure 1, where the average residual value from each child's own mean across days is displayed for each day (± 2 SE). For each session, the mean values for FVC, FEV_1, and FEF_{25-75} exhibit a U-shaped pattern over time in which the average on the first day was larger than the other days. A rapid decrease in function was observed initially, with a subsequent more gradual recovery. This pattern was not observed for peak expiratory flow (PEF), and there was evidence of increasing values in the daily means in the latter portion of the third session.

Methacholine bronchial challenge (MCh) was successfully completed by all subjects in the cohort of 96 children. Thirty-nine children (40.6%) had a positive response (MCh^+). Atopy to one or more of the 10 inhalant allergens noted was observed in 47 of 96 children, or 49% of the cohort. Twenty-one of 96 children (21.8%) had both positive methacholine and a positive atopy assessment.

The influence of MCh^+ on lung function parameters (FVC, FEV_1, and PEF) was examined (Table 5). It was observed that children with MCh^+ tests had smaller mean values for all three lung function parameters after adjusting for age and height. The effect of atopy was observed to have no significant influence on lung function.

Air pollution during the study period displayed day-to-day and diurnal variation. During each of the 2-week camp periods, four distinct pollution events were observed. During these events, maximum 1-hr O_3 concentrations exceeded 100 ppb; 12-hr $[H^+]$ ion concentrations exceeded 100 nmole/m^3. More than half of the particle mass during these events were sulfates. The ambient levels of NO_2 and SO_2 were low, with the maximum 12-hr concentrations of these gases being 10 ppb, and no single hour exceeding 25 ppb. These reflect the remoteness of the camp from local stationary and mobile sources.

The most intense air pollution event began to develop in the late morning of July 24, when O_3 and cSO_4^{2-} concentrations increased sharply. After dropping

Table 3. Pollution episode and corresponding control days.

Session	Episode number	Type of day	Date	Pollution levels[a]		
				O_3 max, ppb	$[H^+]$, nmole/m^3	SO_4^{2-}, $\mu g/m^3$
1	I	Control[b]	June 29–July 3	78	32	9
		Episode	July 6	128	321	49
2	II (a)	Control[b]	July 13–16	79	49	8
		Episode	July 18	133	100	14
2	II (b)	Control[b]	July 13–16	79	49	8
		Episode	July 25	143	559	83
3	III	Control[b]	July 27–31	79	53	14
		Episode	August 6	108	306	54

[a]O_3 max, from highest hourly value 12-hour data set; $[H^+]$ and SO_4^{2-} from Harvard impactor data set.
[b]Maximum value across all control days.

Table 4. Sample size and cohort characteristics by session.

Characteristic	Session I	Session II	Session III	Mean
n = 112	53	32	27	
Age, years[a]	11.6	11.5	11.7	11.6
Height, cm[a]	151	146.2	148	149
Weight, kg[a]	44	41	43	43

[a]Mean values.

slightly overnight, the levels increased again on July 25, reaching a maximum between noon and 1:00 P.M. O_3 concentrations were 143 ppm, particle sulfates (cSO_4^{2-}) exceeded 100 $\mu g/m^3$ with approximately half (47.7 $\mu g/m^3$) in the form of H_2SO_4 (Meloy 285 data). During the most intense portion of the episode, H^+ ion concentrations averaged 550 nmole/m^3.

The correlations between daytime (12-hr) pollutants are presented in Table 6, and indicate a high degree of correlation between PM2.5, SO_4^{2-} and H^+; however,

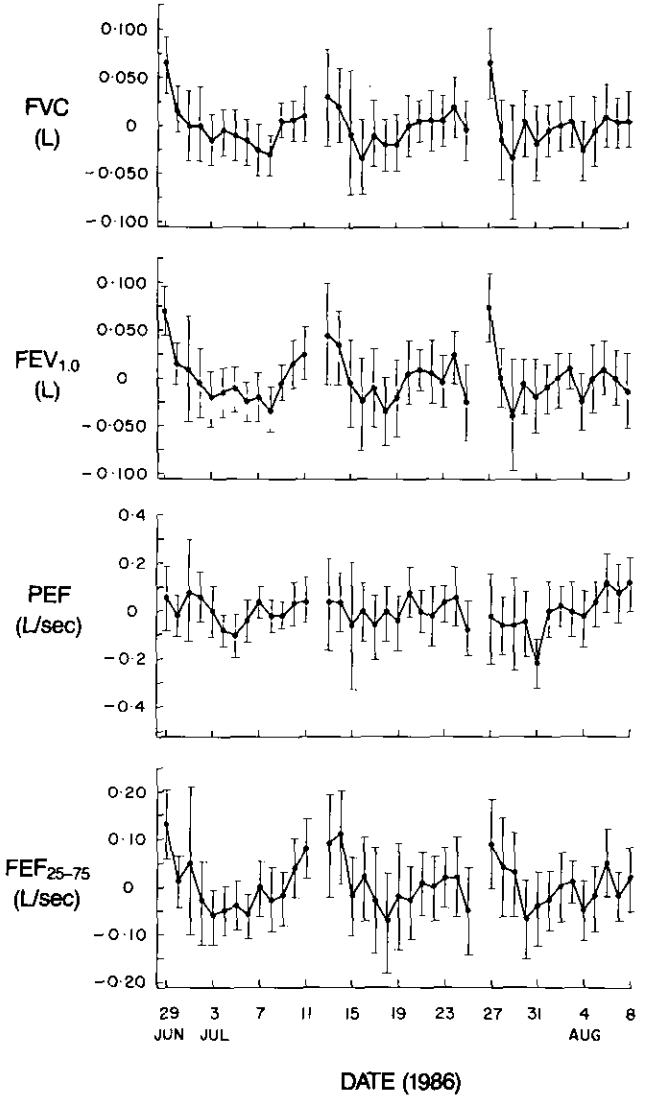

FIGURE 1. Standardized lung function measurements by date. ± (+)/(-), standard errors.

Table 5. Height and age-adjusted mean pulmonary function responses by methacholine responsiveness.

Function	Methacholine MCh−	p[a]	MCh+	Mean
FVC, L	2.66	0.029	2.54	2.62
FEV_1, L	2.36	0.003	2.21	2.30
PEF, L/sec	5.61	0.001	5.18	5.43
n	57		39	96

[a]Two-sided p-value for testing difference between MCh− and MCh+.

Table 6. Pearson correlation coefficients for daytime (12-hr) aerometric data.

	SO_4^{2-}	$[H^+]$	O_3 max	Temperature	Relative humidity
PM 2.5	0.97	0.95	0.78	0.32	0.37
SO_4^{2-}		0.96	0.82	0.30	0.36
$[H^+]$			0.80	0.37	0.29
O_3 max				0.48	0.52
Temperature					0.30

temperature and relative humidity were weakly correlated with the air pollutants and each other. Nighttime correlations were observed to be marginally reduced compared to daytime values. Daytime values are graphically presented in Figure 2. More details on the monitoring data can be obtained from Spengler et al. (*20*).

The influence of air pollution on lung function was examined by comparing children's responses on the day of a major pollution episode to the mean of the responses on corresponding days of low air pollution, termed control days. Table 7 gives the average change in lung function between the episode and the control days for children with positive and negative methacholine responses. A further response, II(c), was defined relating to episode II(b) in Table 6 and is given by the difference between the lung function responses taken the morning after episode II(b) and the average of the control days used for II(a) and II(b). For FEV_1, there was a tendency for the lung function responses on the day of the episodes to be less than the responses on the corresponding control days except for the episode in the third session, in which an increase in function was observed. The children with positive methacholine responsiveness were observed to have larger decrements in function during the episodes than their nonresponsive counterparts (Table 7). A similar pattern was observed for PEF (67–143 mL/sec decline). For both responses (FEV_1 and PEF) the largest decrements were observed on the morning after the July 25 episode in session 2 where FEV_1 declines of 80 mL, and PEF declines of 383 mL/sec were observed.

Discussion

To date, most health studies have reported ambient acid concentrations, primarily H_2SO_4, to be in the range of 2 to 10 $\mu g/m^3$ using the continuous flame

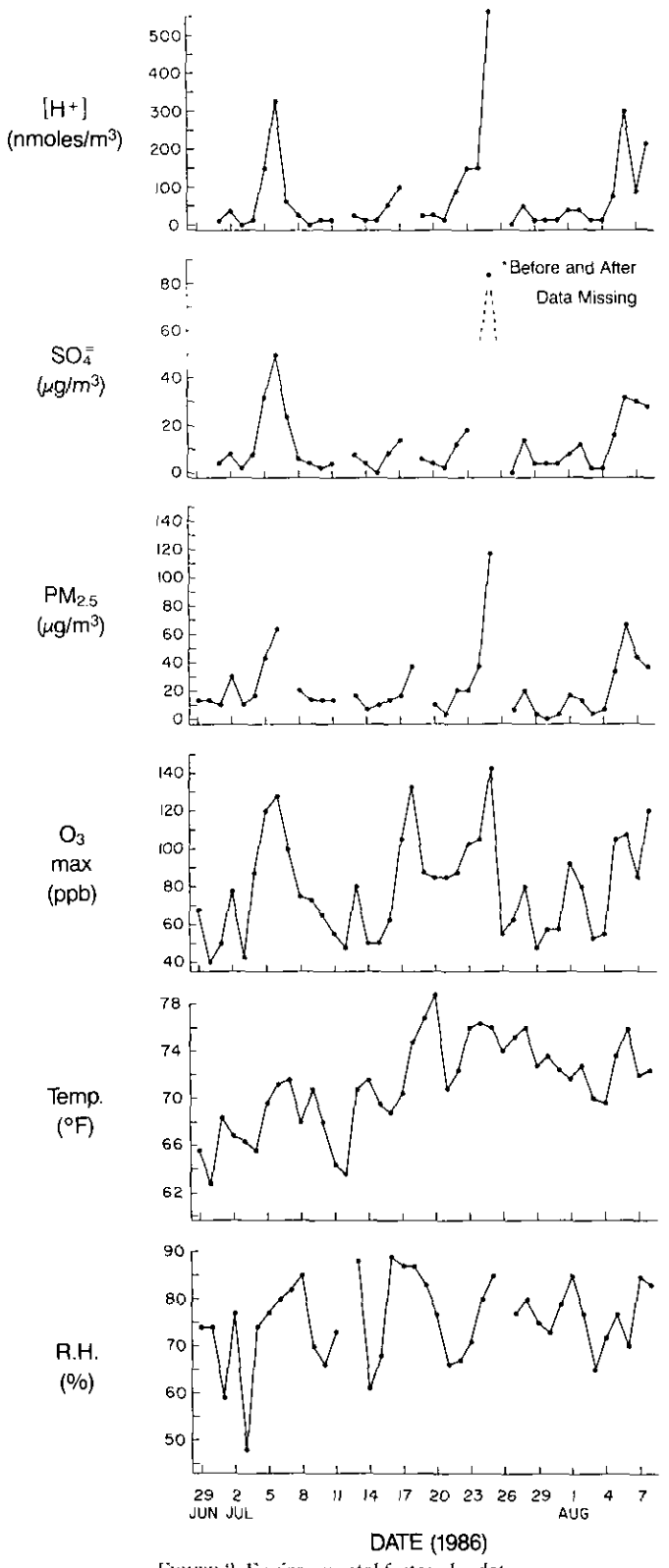

FIGURE 2. Environmental factors by date.

photometric technique and/or equivalent units when the titratable acid method is used (H^+, nmole/m^3). In the present study, continuous ambient acid measurements were observed to attain 47.7 μg/m^3 on one occasion and to exceed 20 μg/m^3 for H_2SO_4 on at least two other occasions during the 41-day summer period. The initial analyses of the effect of episodes on acute pulmonary function indicate that only small changes in pulmonary function may be observed to occur with episodes of air pollution having high concentrations of acid aerosols. Although the magnitude and temporal characteristics of these changes are modest, they appear consistent with other studies where acute and/or persistent declines in lung function are associated with specific air pollutants. The study also demonstrates that frequent and prolonged episodes of relatively high concentrations of acid aerosols do occur in the summer period in Southwestern Ontario.

Lung function measurements throughout the three camp sessions were remarkably stable for all indices. In all three sessions, the first measurement was significantly larger than the mean of the last nine tests. There was evidence that larger, older children produced acceptable data more frequently on the first day. However, when we examined the children with complete data on all days, the difference on the first day remained significant. This suggests that for this study, the first measurement may not be a reproducible value and may not be a representative value of baseline lung function. There is also evidence of a pattern in lung performance, in all three sessions, where the initial values for FVC, FEV_1, and FEF_{25-75} are high, decrease for a few days, and then increase and stabilize for the rest of the session. The pattern differed for PEF, where the measurements appeared stable in the first two sessions but deviated in session 3, when it appeared to progressively increase with time. The third session data are discussed later. There appears to exist a day of camp effect where similar trends in lung measurements by day occur across the three independent sessions. The reason for this trending is not evident, and the influence of this trend will be examined in future analyses.

Table 7. Change in FEV_1 and PEF between episode and control days by methacholine responsiveness.

	FEV_1, mL		PEF, mL/sec	
Episode	MCh− (n = 57)	MCh+ (n = 39)	MCh− (n = 57)	MCh+ (n = 39)
I (July 6)	−34 (0.008)[a]	−48 (0.041)	−79 (0.113)	−67 (0.228)
II (a) (July 18)	−49 (0.022)	−59 (0.170)	30 (NA)	−135 (0.189)
II (b) (July 25)	3 (NA)[b]	−66 (0.144)	−57 (0.270)	−143 (0.218)
II (c)[c] (July 26)	5 (NA)	−80 (0.142)	−91 (0.191)	−383 (0.039)
III (Aug. 6)	10 (NA)	39 (NA)	109 (NA)	211 (NA)

[a]One-sided p-value from one sample t-test to test if change is negative.
[b]NA, p-value not appropriate, since change is positive.
[c]Difference in lung function value between day after episode II(b) and control days.

The influence of a 4-day episode when O_3 concentrations exceeded 150 ppb has been reported to have been associated with decrements in PEF measurements and that this decrement persisted for a period of 5 to 7 days in children attending a summer camp (*7*). Persistent decrements in various lung function indices have also been associated with episodes of total suspended particulates and SO_2 (*12,13*). Although the design of these latter studies differed markedly from those of Lioy et al. (*7*) and from the current study, they all demonstrated a persistent decrement in lung function following an air pollution event. This type of response may account for the low PEF values and the subsequent increase, or recovery, noted in the third session. The PEF data for the third camp were unexpected results. The measurements of PEF in the first few days of session 3 may not have been representative values, as the children came from the Hamilton area, and they would have been exposed to the polluted air mass that affected the region. There is evidence that this air mass extended as far as Toronto (*21*), and Hamilton is situated between Toronto and the camp site. Furthermore, Hamilton is known to have significant local sources of air pollution (*22*), and the pollution profile in the Hamilton region during the event may have been more intense.

In this study, we observed that PEF was decreased on the day of, and on the morning following, the session 2 episode. If we assume a similar response in children originating from Hamilton, and assume a persistent decline to be present when the children arrive for the third session, then the initial PEF data for the third session may be evidence of a persistent decrement and subsequent recovery from the episode that occurred 5 to 7 days previous to the positive trending in the PEF values in the last session. As shown in Figure 2, the pollution profile indicates that O_3 was near the 150 ppb level (143 ppb) and that high aerosol acidity was also present during the July 25 event. Although the association between decrements in PEF and O_3 is significant in the Lioy et al. study, the authors note that other pollutants, including acid aerosols, may have contributed to the persistent decline observed.

Chamber studies have provided evidence that adolescent children, particularly asthmatic children, may be especially sensitive to levels of air pollution periodically observed in various ambient settings. Avol et al. (*4*) exposed children to ambient oxidant air pollution and reported significant decrements in lung function. Koenig et al. (*23*) have reported evidence of decrements in lung function of young asthmatics when exposed to H_2SO_4 aerosols at 100 $\mu g/m^3$. Further preliminary evidence by the same author was presented at this symposium, which indicate altered lung mechanics at concentrations of H_2SO_4 of 68 $\mu g/m^3$ (*24*).

Chamber studies have also demonstrated enhanced pulmonary mechanical responses to SO_2 and O_3 when exposures are coupled to controlled exercise regimes (*21*). Utell (*25*) notes that exercise potentiates pulmonary responses to H_2SO_4 pollutants, particularly in asthmatics. Planned activities during the camp did not include events that required vigorous activity and exertion. The absence of regular, vigorous activity events may have been a significant factor mediating the daily, and episode, lung function responses of the children. At the peak of the July 25 episode, 12 subjects performed pre- and postexercise spirometry (*26*). For the group, postexercise FVC and FEV_1 were observed to increase on control day tests and to decrease on the episode day. The magnitude of this difference, however, was not observed to be statistically different. The expected direction and magnitude of changes in lung function after an air pollution episode appear consistent with evidence of changes in lung function in highly controlled chamber exposure studies to various air pollutants.

Airway hyperresponsiveness is a common characteristic of asthma. However, there is evidence of nonspecific airway hyperresponsiveness being present in nonasthmatic, asymptomatic populations (*27*). In addition, recent evidence has suggested that nonspecific bronchial responsiveness may reflect a predisposition to the development of chronic obstructive lung disease (*28*). We observed that 40% of our nonasthmatic children had MCh^+ tests and that 33% of these children had no histories of chronic respiratory symptoms. We also noted that lung function changes due to the episodes in the MCh^+ group, in the first two sessions, were consistently negative and, in general, larger than the decrements in the MCh^- group.

In Table 7, 8 of 10 lung function responses in the MCh^+ group are negative, while 5 of 10 are negative in the MCh^- group. We further note that after adjusting for age and height, MCh^+ children had lower lung function and greater day-to-day variability (data not given) in all lung function indices when compared to the MCh^- group. These preliminary results do not permit definitive statements on the susceptibility of methacholine sensitive subjects to be made; however, there are indications in these data of differential lung function profiles and responses to air pollutants in children with and without airway hyperresponsiveness. Further analyses are currently directed in examining these differences and their relationships with air pollution.

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